STEERING POST-HARVEST QUALITY OF TOMATO (*SOLANUM LYCOPERSICUM*) WITH LIGHT TREATMENTS

Aino Hämäläinen

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Department of Agricultural Sciences

University of Helsinki

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Tekijä/Författare – Author
Aino Hämäläinen

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Tiivistelmä/Referat – Abstract

Tomatoes (Solanum lycopersicum) are one of the most important food crops in the world. Long supply chains force producers to harvest the fruit before ripening. Ripening then happens in super markets or at the end–consumer. Partly due to the early harvest, tomatoes are perceived flavorless, especially in the wintertime. In addition to a demand for more flavorful produce, consumers are also increasingly interested in healthy food and are looking at the nutritional value of their food before the price tag. As tomatoes are a major crop, they could potentially also contribute to the daily nutrient intake of consumers, such as lycopene, which is i.e. suggested to have preventative qualities towards cancer. Several studies have been conducted to find out how light emitting diodes (LED –lights) could influence the plant and its compounds during growth, but post-harvest research to a lesser extent. Research on post-harvest LED–lighting suggests that quality attributes could also be influenced post-harvest. Important parameters to look at are color and firmness, as they are what buying decisions are primarily based on. Further, lycopene, but also total soluble sugars (TSS) and titratable acidity (TA), and especially their ratio, which defines how tomato flavor is perceived, are worth studying. Therefore, this study aimed to find out, how LED–light treatments could be used to steer the post-harvest quality of tomatoes.

Three continuous light treatments were used; Blue, far-red, a standard growing light with high red to far-red ratio and dark as control. The study was done on two cultivars by measuring TSS, TA, lycopene, vitamin C and firmness of the tomatoes every fourth day for 12 and 15 days. Additionally, a set of tomatoes was analyzed for changes in weight and color.
The results suggest that LED-lights do influence the quality characteristics of tomato fruit.
Blue light seemed to decrease firmness, but to increase lycopene. Lycopene accumulation was also enhanced by a high red to far-red ratio, whereas far-red had a reversing effect. Both blue and high red to far-red ratio treatments increased the chroma values, making the tomatoes brighter in color. Far-red seemed to enhance red color development and to retain firmness, but to decrease lycopene accumulation and to make the color duller. Tomatoes kept in the dark had low lycopene content and a dull coloration. Results on TSS and TA indicate differences in genotype responses, which further underlines the need for further research on the topic and especially the effect of cultivar.

The results of the study indicate that tomatoes should not be kept in the dark during storage, as then the full potential of their external and internal quality will not be reached. High red:far-red ratio lighting increases lycopene and brightens the coloration, and could be considered to be used during storage. However, other external factors affecting quality, such as ethylene and temperature, should be included in the future research to study their effect and correlation with light in regard to tomato fruit quality.

Avainsanat – Nyckelord – Keywords
LED light, post-harvest, tomato, solanum lycopersicum, lycopene, brix, TSS, Titratable Acidity

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Tiivistelmä/Referat – Abstract

Tomaatti *(Solanum lycopersicum*) on yksi maailman tärkeimmistä ruokakasveista. Pitkät tuotantoketjut kuitenkin pakottavat viljelijät keräämään hedelmät ennen täyttä kypsymistä. Kypsyminen tapahtuu täten ruokakaupoissa ja kuluttajan kotona. Osittain siksi, että tomaatit kerätään aikaisin, kuluttajat mieltävät ne erityisesti talvikaudella mauttomiksi. Maukkaamman ruoan kysynnän lisäksi kuluttajat ovat kiinnostuneita terveellisyydestä ja tarkkailevat ruokansa ravintoarvoja hinnan sijaan. Tomaattien suuri kulutus voisi mahdollisesti edistää kuluttajien vitamiinien ja mineraalien kulutusta, kuten esimerkiksi lykopeenin, jolla on arveltu olevan syöpääehkäiseviä ominaisuuksia.
Useissa tutkimuksissa LED -valojen on huomattu vaikuttavan kasvien yhdisteisiin kasvun aikana, mutta sadonkorjuunjälkeistä vaikutusta on tutkittu vähemmän. Sadonkorjuunjälkeisten tutkimusten tulokset ovat kuitenkin osoittaneet, että laadullisiin ominaisuuksiin voitaisiin vaikuttaa myös hedelmien keruun jälkeen. Tärkeimpiä laadullisia ominaisuuksia tomaatissa ovat väri ja kiinteys, sillä kuluttajat tekevät ostopäätöksensä pääasiallisesti niiden mukaan. Muita tärkeitä, tutkimisen arvoisia laatutekijöitä ovat lykopeeni, c-vitamiini, liukoiset sokerit sekä titrattava happamuus, ja kahden viimeisen suhde, jonka on huomattu vaikuttavan makukäsitykseen. Tässä tutkimuksessa keskityttiin selvittämään, kuinka LED-valokäsittelyitä voitaisiin käyttää tomaatin laatutekijöiden säätelyyn varastointivaiheessa.

Tutkimuksessa käytettiin kolmea valokäsittelyä: sinistä, kaukopunaista, standardi-kasvatusvaloa korkealla punaisen ja kaukopunaisen suhteella sekä pimeää kontrollikäsittelynä. Kokeet tehtiin kahdelle tomaattilajikkeelle, ja niistä mitattiin liukoiset sokerit, titrattava happamuus, C-vitamiini, lykopeeni sekä kiinteys joka neljäs päivä 12 ja 15 päivän ajan. Lisäksi, kymmenestä tomaatista kummastakin lajikkeesta analysoitiin painon ja värin muutokset varastoinnin aikana.

Tulosten perusteella LED-valot vaikuttavat tomaatin laatutekijöihin. Sininen valo teki tomaateista vähemmän kiinteitä, mutta lisäsi lykopeenipitoisuutta. Lykopeeni lisääntyi myös korkealla punaisen ja kaukopunaisen valon suhteella, kun taas kaukopunainen rajoitti lykopeenin kertymistä. Sininen valo ja standardivalo myös nostivat chroma-arvoja kirkastaen tomaattien väriä. Kaukopuna vaikutti lisäävän punaista väriä ja pitävän tomaatit kiinteinä, mutta piti värityksen himmeämpänä. Liukoisten sokerien ja titrattavan happamuuden tulokset viittasivat lajikkeiden välisiin eroihin valon vaikutuksessa, mikä puolestaan korostaa lisätutkimuksen tarvetta ja erityisesti lajikkeen merkityksen selvittämistä.

Tulokset osoittavat, että parhaan mahdollisen laadun saavuttamiseksi tomaatteja ei tulisi säilyttää pimeässä sadonkorjuun jälkeen. Korkea punaisen ja kaukopunaisen valon suhde lisäsi lykopeenia ja kirkasti väriä, ja tämänkaltaista valoa voitaisiinkin suositella käytettäväksi varastoinnin aikana. Muut ympäristötekijät, kuten esimerkiksi etyleeni ja lämpötila tulisi kuitenkin ottaa huomioon seuraavissa tutkimuksissa, ja erityisesti niiden vaikutus ja korrelaatio valon kanssa tomaatin laatuun suhteutettuna.

Avainsanat – Nyckelord – Keywords
LED-valo, post-harvest, tomaatti, solanum lycopersicum, lykopeeni, liukoiset sokerit, titrattava happamuus

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Contents

Glossary

AsA	Ascorbic Acid
DHA	Dehydroascorbic Acid
DM	Dry Matter
d/n	Day/Night
DW	Dry Weight
FW	Fresh Weight
LED	Light-emitting diodes
R:FR	Red to far-red ratio
RH	Relative Humidity
ROS	Reactive Oxygen Species
TA	Titratable Acidity
TSS	Total Soluble Sugars, °Brix

1 Introduction

Tomatoes (*Solanum lycopersicum*) are one of the most important horticultural crops worldwide. Globally, the US and China are the largest producers, and in Europe the big players are the Netherlands, Spain and Italy. Due to the high demand and long supply chains, it is of great importance to optimize and maintain quality. Quality is however challenging to define, and the definition is different for the different parts of the supply chain; grower, distributor, and the end-consumer. Pre-harvest quality is mostly concerning the grower, whereas post-harvest quality is important especially for the distributor and the consumer. Breeders and growers are mainly interested in yield and in regards of post-harvest quality, in firmness and color of the fruit, as these are the two primary criteria for the consumers' buying decision. Consumers are additionally interested in flavor, which is why the preceding parts of the chain should pay also attention to inner quality; people will buy the good-looking tomato once but will not buy it for the second time, if the flavor is not perceived as good.

Post-harvest quality can in general be thought to comprise of color, firmness, flavor, and mouthfeel. These sensory qualities are often determining the purchase. Additionally, nutritional value is becoming increasingly important as consumers are becoming more interested in the healthiness of the produce they buy, as well as in functional products (products that have increased nutritional value). Being able to steer the nutritional content of fresh products could therefore potentially increase the nutrient intake of consumers but also be used for marketing these products.

The nutritional value of tomatoes can be influenced already during cultivation through mineral nutrition, temperature, and light quality, but as tomatoes have long supply chains, they are often harvested before the full accumulation of the nutritional compounds.

The current market situation and consumer perception indicate that the general quality could be improved. Attempts to increase both agronomical and sensory quality have been made with the help of LED-lights, but so far this has mainly concerned pre–harvest activities. Some research has, however, also been aimed towards post-harvest research, and the results clearly suggest that post-harvest light treatments could be used for steering quality characteristics in tomatoes, but the differing conclusions also illustrate a need for further research and a clear

gap in knowledge. As this knowledge would be of great value for all parties of the supply chain and would result in a longer shelf life, tastier and healthier tomatoes and fewer losses, this study aimed to find out whether post-harvest quality characteristics of tomatoes could be influenced with the use of supplemental LED-lights during storage. Thus, the present study, funded by Maiju ja Yrjö Rikalan puutarhasäätiö, in co-operation with the Finnish Natural Resources Institute (Luke) and the University of Helsinki, concentrates on how the quality of tomatoes could be influenced with supplemental post-harvest LED-light treatments.

2 Literature review

2.1 Tomato quality characteristics

Tomato is a climacteric fruit, meaning that ripening processes and ethylene production continue after harvest, and that they are very sensitive to exogenous ethylene. Climacteric characteristics allow harvesting mature fruit, which are not in their fully ripe stage, which further makes longer supply chains possible. However, ethylene production and sensitivity in tomato set challenges for the supply chain, as when the ripening continues, also the respiration increases, resulting in loss of firmness.

Harvesting of tomatoes is typically done according to their color, as it is considered to be a good indicator for maturity. Color at mature stage varies between cultivars, but for example USDA (United States Department of Agriculture) and others have published color charts (Figure 1), which in general can be used to distinguish if the tomato is ready for harvest. Most often tomatoes are harvested at stages 3 (turning) or 4 (pink) and sold when they are in stage 4 (pink) or 5 (light red), to provide a possibility for a longer supply chain.

Stage	Color	Description
1	Green	The surface is completely green in color. The shade of green may vary from light to dark.
2	Breakers	There is a definite "break" in color from green to tannish–yellow, pink, red on <10% of the surface
3	Turning	10–30% of the surface shows a change in color from green to tarnish–yellow, pink, red or a combination thereof
4	Pink	30–60% of the surface shows pink or red in color
5	Light red	60–90% of the surface shows pinkish–red or red
6	Red	More than 90% of the surface is red

Figure 1.Tomato color chart (Adapted from USDA (1991)).

In addition to visual observation, color can also be defined with a colorimeter. There are several ways to define color, but often coordinates L* (+Light/–Dark), a* (+Red/–Green) and b* (+Yellow/–Blue) are used (Konica Minolta 2018). Based on these coordinates, hue angle (H, Formula 1), and chroma (C, Formula 2) can be calculated.

$$H = \tan^{-1}\left(\frac{b*}{a*}\right) \quad (1)$$

$$C = \sqrt{a*^2 + b*^2} \quad (2)$$

Hue angle defines the relation of red and green to blue and yellow and has been seen to give good estimations on the marketable color for tomatoes. The hue angle of tomato decreases (the fruit becomes more red) during ripening, as seen in Table 1. For a ripe tomato, the preferred hue angle is around 40 (Cantwell 2018). Chroma defines the brightness and dullness of the tomato, with higher C -values indicating brighter color, whereas lower values present duller coloration. Further, these values can be used as indicators for good color. Most tomatoes become more red during ripening, and therefore a* and especially a*/b* values can be used to observe the red color development during ripening (Brandt et al. 2006; Barrett & Anthon 2008).

Table 1. L*a*b* coordinates and lycopene content for different stages of tomato (Adapted from Cantwell (2010)).

Stage of development	**Ripening stage**	**L***	**a***	**b***	**Hue**	**Lycopene (mg/kg FW)**
Mature–Green	1	62.7	–16.0	34.4	115.0	0.1
Breaker	2	55.8	–3.5	33.0	83.9	0.4
Pink–Orange	4	49.6	16.6	30.9	61.8	8.6
Orange–Red	5	46.2	24.3	27.0	48.0	16.8
Red; Table–ripe	6	41.9	26.4	23.1	41.3	30.7.
Dark Red; overripe	6+	39.6	27.5	20.7	37.0	36.9

During ripening the color of most tomatoes becomes increasingly red, and it is known that the development of red color correlates strongly with the lycopene content (Shi & Le Maguer, 2000). Lycopene is a carotenoid pigment, which is the main contributor for red color in tomatoes. Several studies have suggested lycopene to be preventative for i.e. prostate cancer and to promote cardiovascular health through scavenging reactive oxygen species (ROS) and reducing cholesterol synthesis (Story et al. 2010).

It seems that most of the lycopene is found in the skin of tomatoes (McCollum, 1955 ref. Shi & Le Maguer 2000). In tomato, there is about 4 mg/100 g FW of lycopene, according to the National Institute for Health and Welfare of Finland (THL 2018), but this seems to be dependent on the cultivar and development stage of the tomato, and can vary from 0.72–20 mg/100 g (Beerh & Siddappa 1959; Gross 1987; Mangels et al. 1993 ref. Shi & Le Maguer 2000). Lycopene accumulation starts after chlorophyll degradation simultaneously with ripening and is affected by environmental factors. Higher light intensity promotes lycopene accumulation (Jarquín-Enríquez et al. 2013), but the rate seems to be cultivar dependent (Schouten et al. 2014). Chlorophyll degradation and lycopene accumulation have also been observed to be temperature sensitive and seem to be faster in higher temperatures. However, above 30 °C lycopene synthesis is restricted (Tomes 1963; Brandt et al. 2006), whereas in temperatures 4–8 °C lycopene might start breaking down (Schouten et al. 2014). Therefore, it is of importance to control the temperatures during the growth, but also during post-harvest, when cooling of fruit takes place.

Other interesting compounds found in tomatoes are vitamin C and different flavonoids. Vitamin C is the active form of ascorbic acid, and it is needed in several functions of the body, i.e. in supporting the functions of the immune system, protein metabolism, and wound healing (National Institutes of Health 2018; WebMD 2018). The recommended daily intake of vitamin C is 80–100 mg for an adult person (EFSA 2013). In tomatoes, there is about 14.1–25 mg/100 g FW of vitamin C (THL 2018; NEVO 2019), but the quantity is largely dependent on the cultivar and development stage of the tomato. Flavonoids are a group of phytochemicals found in many fruits and vegetables considered to be beneficial for health (Szalay 2015). In tomatoes, quercetin has been observed to be one of the major flavonoids

(Periago et al. 2002; Peng et al. 2008), and it has been seen to accumulate during ripening (Bhandari & Lee 2016). The levels of quercetin seem to be depending on the genotype (Crozier et al. 1997), but estimated amounts of quercetin are around 10–20 µg/100 g FW (Bhandari & Lee 2016; Zanfini et al. 2017).

The nutritional concentration as well as other quality characteristics are determined by preharvest factors, for example growing conditions (nutrient availability, temperature, light) and genotype, but also post-harvest conditions. As the nutritional value of products has become more important for consumers (Gagliardi 2015), it is of great importance to know if the accumulation of nutritional compounds found in plants could be affected post-harvest.

Most often nutritional values cannot, however be tasted, and what makes a good flavored tomato, is seen to be characterized by the sugar content and acidity, and more specifically their ratio. Total soluble sugars (TSS), measured in °Brix , are an indicator of sweetness in tomato, as in general it is thought that the TSS in tomato are mostly comprised of glucose and fructose, and especially higher fructose content compared to sucrose gives sweeter flavor (Beckles 2012; Watkins 2017).

Sweetness in tomato is firstly defined by genetic factors but also pre– and post-harvest treatments, and increases during ripening (Helyes et al. 2006). Total soluble sugars can range from 3 °Brix in large tomatoes to even 15 °Brix in smaller cherry tomatoes (Beckles 2012).

Titratable acidity (TA) in tomatoes is mostly citric acid and malic acid (Shi & Le Maguer, 2000). It is thought that the higher their ratio, the better tasting the tomato is.

2.2 Shelf life characteristics and post-harvest technology

The general purpose of post-harvest activities is to prolong the shelf–life of the product without compromising the quality. Through post-harvest activities the aim is to reduce metabolic processes and water loss and to prevent any undesirable changes in the fruit, such as softening and discoloration. Further, minimizing damage, both mechanical and microbial, and preventing chilling and freezing injuries is essential (Watkins 2017).

Shelf life of tomatoes, in general, depends on the maturity and ripeness of the fruit at harvest. In optimal conditions, green tomatoes can last even for 28 days, whereas the marketed pink for 7–14 days and red tomatoes only for 2–4 days (Boyette et al. 1997). The challenge is that most tomatoes are marketed in the later stages (pink, light red), when their shelf life is already shorter, but the supply chain would need the fruit to remain marketable for a longer period.

As tomatoes are living organisms, their metabolic processes continue also after harvest and inevitably there are changes in the quality of the fruit. In tomatoes, β–carotene and lycopene concentrations increase during ripening contributing to the increasing red color, while the cell turgor is compromised due to water loss. This further causes decreased firmness, and the sugar to acid ratio, which is seen to have a significant role in the flavor perception (Cantwell 2018) changes. Typically, the quality of produce does not improve after harvest. Therefore, maintenance of quality is the main task of post-harvest actions. This is done through gentle handling and by optimizing storage conditions. Shelf life of tomatoes is depending on the stage of their maturity at harvest, and the same applies to the optimal storage conditions. However, in general, the temperature should be kept around 10–15 °C (Beckles 2012) with a relative humidity (RH) at 85–95 % to prevent excessive evapotranspiration (Boyette et al. 1997). For unripe tomatoes, lower than optimal temperatures (<13 °C) can cause poor coloring, and with ripe tomatoes softening and decay may occur (Kader 2002 ref. Watkins, 2017). Controlled atmosphere (CA) and modified atmosphere (MA) storages with increased CO_2 and decreased O_2 are often used to control the gaseous concentrations, and the concentrations depend on i.e. fruit size and maturity, but also storage temperature. The gaseous concentrations in storage facilities should optimally be around 3 % O2 and <3 % CO2 to prevent excessive respiration (Cantwell 2018).

Using 1–MCP (1–Methylcyclopropene) is a new technology in post-harvest treatments of various fruit. It works through binding to ethylene receptors and inhibits in this way ethylene from synthesizing (Watkins 2017). 1–MCP is also suggested to prevent TA degradation during ripening and through this maintain a higher TSS:TA ratio, while not affecting TSS values directly (Beckles 2012).

Other technologies used to maintain post-harvest quality include the use of light. UV–B and UV–C are some of the light treatments used for post-harvest, and they are suggested to have

potential in increasing i.e. anti–oxidants and TSS in addition to having pathogenic protection characteristics (Beckles 2012).

2.3 LED–light treatments

New studies suggest that post-harvest factors could, in addition to maintaining quality, also steer the quality of the fruit as well, and in this way influence the quality of the end-product and its shelf life. One rising technology for post-harvest quality maintenance, and even improvement, is the use of light-emitting diodes (LED's). LED lights are used increasingly, as they do not emit heat, are adjusted easily, and are longer-lasting than for example high-pressure sodium (HPS) lamps.

It is known that the wavelength of light affects the growth and development of plants. For example, red light is known to promote germination and leaf formation, but research has shown it could also enhance the concentration of anti-oxidants and phenolic compounds (Bliznikas et al. 2012). Blue light, in addition to i.e. having a major role in the stomatal functioning of plants and increasing plant pigmentation (Qingwu & Runkle 2017), has been observed to elevate the vitamin C content as well as increase the antioxidants in plants c.

Research has so far focused largely on the effects of pre-harvest LED lights, but post-harvest LED-light treatments are of increasing interest. Panjai et al (2017) concluded that among others lycopene and total flavonoids were increased when tomatoes were treated with red light. This was also the conclusion of Alba et al (2000) as well as Dhakal and Baek (2014). Furthermore, far-red light seemed to have a reversing effect on increasing lycopene (Alba et al. 2000), suggesting that lycopene synthesis is linked to phytochrome activity. This is supported by the findings of Nájera et al (2018), where the lycopene content appeared to be higher with a high R:FR ratio. In the same study, TA was observed to be higher with the increased R:FR ratio, although it was suggested that both TSS and TA concentrations are largely cultivar dependent.

The effects of light on the TSS concentrations have controversial observations. Some studies suggest that red light has a positive effect on the TSS accumulation at least to some extent;

either with only red (Panjai et al. 2017), with combination of red and far red (Nájera et al. 2018), or a combination with red and blue (Lei et al. 2016), whereas others could not find differences between light treatments used (Alba et al. 2000; Dhakal & Baek 2014).

Firmness, another important quality factor of tomatoes, has also had differing observations with post-harvest LED treatments. Alba et al (2000) did not observe the firmness to be affected by light, whereas Nájera et al (2018) observed increased firmness with a high R:FR ratio.

Lei et al (2016) observed higher vitamin C concentrations with tomatoes treated with blue light. Blue light has also observed to delay color change – which could potentially promote longer shelf life (Dhakal & Baek 2014). However, in peaches blue light treatment induced ripening process through stimulating ethylene production, possibly indicating increased stomatal activity (Gong et al. 2015).

3 Research objectives

The objectives of the present study were to find out whether the post-harvest quality of tomatoes (*Solanum lycopersicum*) could be influenced with supplemental LED-lights during storage. The research aimed to see, if outer quality, weight and color would be affected by different spectra of light. Further, the effect of post-harvest LED-lights on chosen nutritional compounds (vitamin C, lycopene, total soluble sugars and titratable acidity) was studied to see, if the internal quality of tomato could be influenced.

Two cultivars of tomato were used to evaluate on the role of genetics on the responses to light. Additionally, a greenhouse experiment was conducted to assess the effect of higher temperature and high-pressure sodium lighting on weight and development of color.

4 Materials and methods

The experiment was performed in one storage chamber divided in two parts with two cultivars, totaling in two separate sets of data, one for each cultivar. For the cultivar 'Audience' the experiment lasted for 12 days including four different time points (Days 0,4,8 and 12) for sampling and analyses. For the cultivar 'Livento', an additional time point at 15 days was added.

4.1 Plant material

Two cultivars of tomato (*Solanum lycopersicum)* were used in the experiment, 'Audience' and 'Livento'. These popular cultivars are in general thought to be tomatoes with good flavor characteristics. The fruit was harvested ('Audience' 28.9.2018, 'Livento' 12.10.2018) at turning/pink stage three days before the first analysis day and stored in dark cool storage (12 °C for 'Audience', 7 °C for 'Livento'). In the beginning of the experiment, the two cultivars had differing development stages, with 'Livento' being more mature than 'Audience' (Figure 2). The tomatoes were obtained from a commercial grower (Hortiherttua Oy, Karjalohja, Finland), where the tomatoes had grown in a greenhouse (23/17 °C d/n, RH 75 % for 'Audience', 22/16,5 °C d/n, RH 86 % for 'Livento') with no supplemental lighting (Daylength during cultivation ~12 h for 'Audience' and ~10 h for 'Livento').

Figure 2. Tomatoes used in the experiment on day 0. a) 'Audience' and b) 'Livento'.

4.2 Treatments

The tomatoes were treated in one storage chamber on shelves equipped with LED lights. The storage room had two separate shelf units on both sides. The experiment consisted of three light treatments and a dark control treatment. Each treatment was on a separate shelf, replicated twice. The light intensity (PAR) was set to be 50(±5) µmol/m^2/s and the lights were kept on continuously throughout the experiment. Three different LED lights (Valoya Oy, Helsinki, Finland) were used in this experiment:

- AP673L, standard light with high R:FR ratio (Blue 12 %, green 19 %, red 61 %, far-red 8 %)
- FR, Monochromatic far-red
- S4, Monochromatic blue

As a control, one set of tomatoes was kept in the dark with no additional light.

The storage shelves (Figure 3) were surrounded with white plastic foil to prevent radiation contamination between the treatments. Additionally, a black plastic foil was placed to divide the room. The tomatoes were placed on individual pieces of corrugated cardboard, which were turned 90° every second day to ensure even light distribution. Following each sampling, the tomatoes remaining in the chamber were randomized within the treatment.

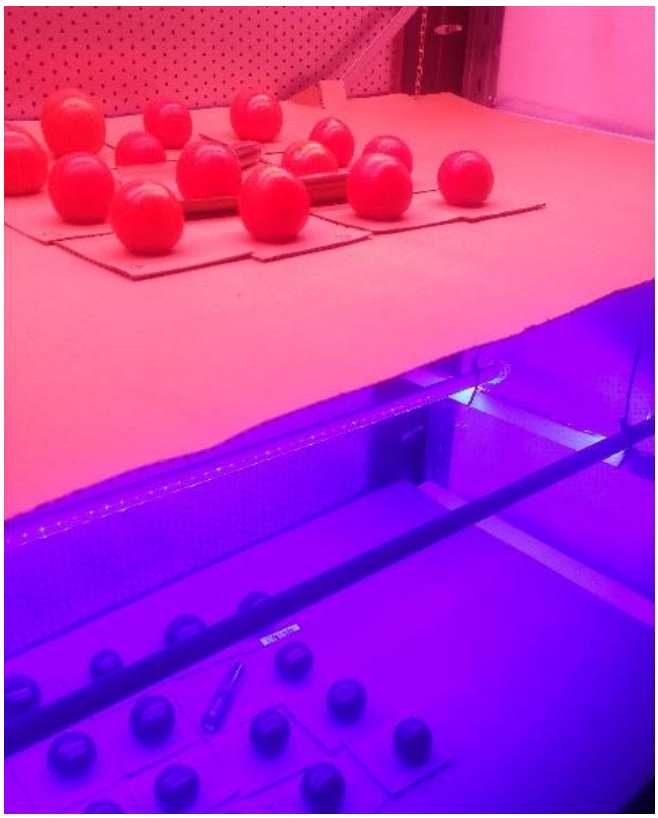

Figure 3. Tomatoes on storage shelves on corrugated cardboard.

The temperature in the chamber was set to 14 °C. Temperature and relative humidity were followed with dataloggers (EasyLog EL-USB-2-LCD, Lascar Electronics, UK), which were placed on the shelves together with the tomatoes. The experimental setup was randomized using a randomized complete block design (RCBD) with two blocks (Figure 4).

Shelf unit left	
Control - dark	Monochromatic B
Monochromatic FR	Standard - AP673L

Shelf unit right	
Monochromatic FR	Standard - AP673L
Monochromatic B	Control - dark

Figure 4. Experimental setup inside the chambers.

4.3 Sampling

For weight and color analyses a set of ten tomatoes/treatment/cultivar was used, with five tomatoes/block. This set of individually labeled “observation tomatoes” was analyzed every fourth day for changes in weight and color throughout the experiment.

For the other quality analyses, an initial measurement of 10 tomatoes was analyzed (Day 0). Following this, two subsamples of five tomatoes from each experimental unit (shelf) were measured every fourth day resulting in four samples/treatment/sampling moment, and three sampling moments for the cultivar ‘Audience’ (Days 4, 8, 12) and four for the cultivar ‘Livento’ (Days 4, 8, 12, 15). The two subsets of five tomatoes were randomly chosen within the experimental units.

4.4 Greenhouse experiment

In addition to the experiment conducted in the storage chamber, a set of ten tomatoes from the cultivar ‘Livento’ were placed in a greenhouse (18.5±0.6 °C, RH 58±8 %) with HPS–lighting.

The tomatoes were analyzed for their color and weight on days 0 and 15. Further, their dry weight was measured on day 15 to evaluate the relative water loss compared to the LED-light treatments.

4.5 Analyses

4.5.1 Non–destructive analyses

The weight of ten labelled tomatoes from each treatment was measured every fourth day with an accuracy of two decimals. Change in weight (%) was calculated with the following formula:

$$\frac{W1 - W2}{W2} * 100 \quad (3)$$

where

W1 = Weight (g) from previous measurement

W2 = Weight (g) from current measurement

The color of the same tomatoes was measured using a colorimeter (Minolta CR–300, Konica Minolta Sensing Europe B.V.) by first calibrating with white and then taking three measurements (top and both sides) and noting down the results in L*, a*, b* coordinates. From these coordinates the chroma and hue values were calculated as described in chapter 2.1. Additionally, the tomatoes used in the color analyses were photographed (Canon EOS–M, 18–55mm lense, Canon Inc., Tokyo, Japan) every four days for visual observation of possible changes.

4.5.2 Destructive analyses

All inner quality measurements were performed in duplicate on days 0,4,8, and 12. For 'Livento', measurements were additionally done on day 15.

After firmness measurements, samples were first homogenized with a blender (Bosch ErgoMixx 750W). From the homogenized sample 1 gram was taken for the lycopene analyses. The rest of the homogenized sample was filtered (Quantitative filter paper, 454, 12–15 µm, VWR International, France) for the TSS, TA and vitamin C analyses.

4.5.2.1 Firmness

Firmness of the cultivar 'Livento' tomatoes was measured with a handheld penetrometer (Digital fruit hardness tester, STEP Systems GmbH, Nuremberg, Germany) using the peak hold measurement and an 8 mm tip (i.e. García et al., 1995). The firmness was measured

every fourth day from the tomatoes used in the inner quality analyses. From the results the change in weight (%) was calculated (Formula 4).

$$\frac{F1-F2}{F2} * 100 \quad (4)$$

where

F1= Firmness from previous measurement

F2 = Firmness from current measurement

4.5.2.2 Total soluble sugars

Total soluble sugars (TSS) were measured from the blended and filtered sample with a hand–held refractometer (Master α refractometer, Atago, Japan) by dropping a small amount of the filtered sample on the lense and noting down the results expressed as °Brix.

4.5.2.3 Titratable acidity

The amount of titratable acidity was analyzed with a standard method (Garner et al. 2019; UC Davis 2019) with some modifications. A filtered sample of 5 g was measured to a 50 ml centrifuge tube, and 25 ml of distilled water was added. The titration was performed with a Mettler Toledo titrator (T70 with a Rondo Tower, GWB Switzerland) by titrating the samples up to a pH of 8.1. with 0.1 M NaOH and calculating the amount of citric acid (w/w) in the samples (formula 5).

$$TA\% = V * N * meqv * 100/v \quad (5)$$

where

V= Amount of base used (ml)

N= Normality of base (0.1 N)

meqv = Milliequivalent factor (0.064 for citric acid)

v= weight of non-diluted sample (g)

4.5.2.4 Vitamin C

Vitamin C content was analyzed through a redox iodometric titration method (University of Canterbury, 2018 with modifications), where ascorbic acid is oxidized into dehydroascorbic acid with iodine using a starch solution as indicator. One ml of the filtrated sample was added to 2 ml of starch solution, where after iodine solution was added until a definite color change was observed, and the amount of iodine used was recorded. The amount of ascorbic acid in the sample was calculated (formula 6) based on the amount of iodine needed for the color change in the sample as compared to the amount needed in the standard. The vitamin C analyses were done with three replicates.

It is to be noted, that the quantity of titrating solution consumed is similar to the quantity of ascorbic acid.

$$AAsa = (Tsa / Tstd) * AAstd \quad (6)$$

where

AAsa = Ascorbic acid content of sample (mg/ 100 ml)

Tsa = Average consumption of titrating solution per sample (ml)

Tstd = Average consumption of titrating solution in standard solution (ml)

AAstd = Ascorbic acid content of standard solution (mg/ml)

4.5.2.5 Lycopene

Lycopene content was analyzed with UV–VIS spectroscopy (Shimadzu Corporation Japan, UV–1800 240V, Canbury, OR, USA) with a method following the principles of Alda et al, (2009) and Anthon and Barrett (2018) with modifications.

From the homogenized material one gram was added to 25 ml of hexane:ethanol:acetone mixture (2:1:1) in a 50 ml centrifuge tube. The sample was then placed on a rotary mixer for 30 minutes. After this step, 10 ml of distilled water was added, and the sample was agitated for another 2 minutes and left to sit for the separation of polar and non–polar layers. Absorbance of lycopene was measured at 503 nm from the hexane layer of the sample. The amount of lycopene (mg/100 g) was calculated (formula 7).

$$((A * 537 * V * hmf)/(W*172))/10 \quad (7)$$

where

A= absorbance (nm)

537 = lycopene weight (M)

V= sample volume (ml)

hmf = hexane multiplication factor (0.55)

W= sample weight (g)

172 = extinction coefficient

4.5.3 Statistical analyses

For statistical analyses SPSS (version 24, IBM Corp, Armonk, NY, USA) was used. The results were analyzed with a one-way ANOVA and repeated measures ANOVA to see, whether there were differences between the different treatments, and between the different time points with pairwise comparison analyses. Additionally, regression analyses were performed to find out possible correlations between the variables. A threshold of P-value 0.05 was used in all the analyses to define statistically significant differences.

5 Results

5.1 Non-destructive analyses

5.1.1 Weight

Weight of the tomatoes decreased steadily in both cultivars, with a more rapid decrease in ‘Audience’ than ‘Livento’ (Figure 5). In ‘Audience’, significant differences (P=0.005) could be seen after four days in storage, when tomatoes from the dark treatment had a significantly higher weight decrease than tomatoes from far-red (P=0.007) and AP673L (P=0.022) treatments, with the same trend continuing after eight days in storage. In ‘Livento’, however, the only statistically significant difference could be observed between days 12 and 15, when fruits in far-red treatment had a significantly more rapid decrease in weight than in the dark treatment (P=0.013).

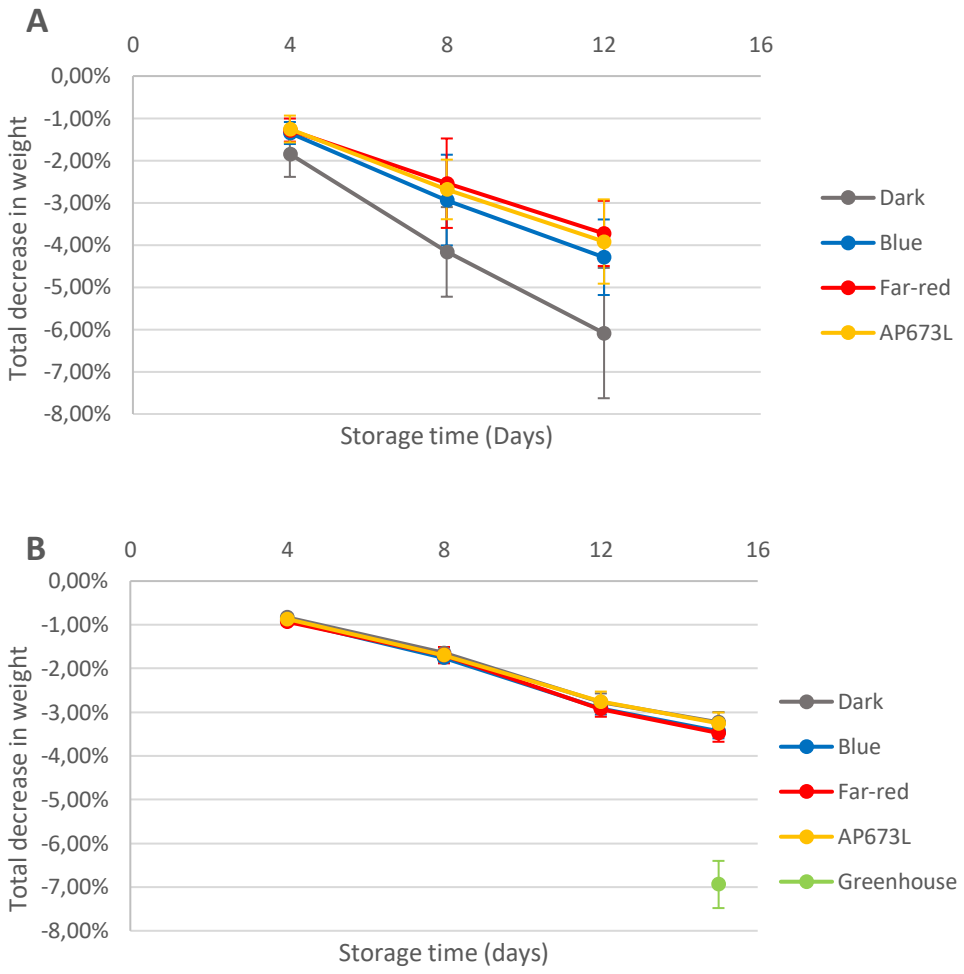

Figure 5. Percentual weight decrease in a) 'Audience' and b) 'Livento'. Error bars representing standard deviation. N=10.

The fresh and dry weight of ‘Livento’ was recorded after day 15, and dry matter percentage was calculated. The dry matter percentage was on average 5,5(±0,2) % and no significant differences could be observed between the treatments.

5.1.2 Color

a/b* –values*

The a*/b* ratio increased in both cultivars over time (Figure 6), indicating that the tomatoes were becoming more red. In ‘Audience’, the tomatoes from the far-red treatment had a significantly lower a*/b* value than the dark treatment on day 4 (P=0.026), but on day 12 they had the highest value (P=00.019). Also, in ‘Livento’ tomatoes from the far-red treatment had higher values toward the end of the experiment (P=0.000), but this was only significantly higher than in the tomatoes from the blue treatment, which had significantly lower a*/b* values throughout the experiment from the treatments, apart from the greenhouse treatment on day 15.

Looking at the color development within the treatments between the days, it could be seen that in ‘Audience’ the a*/b* ratio increased significantly between all the time points. In ‘Livento’, the increase was significant in all treatments apart from the blue treatment between days 12 and 15.

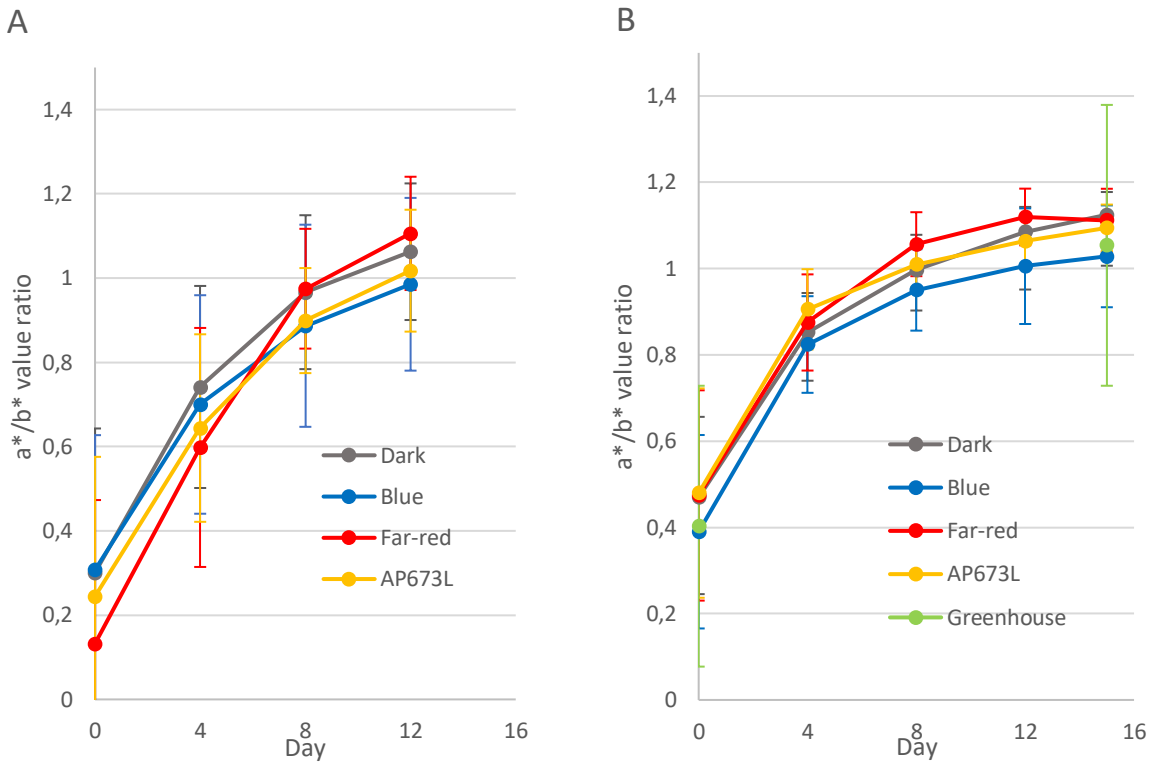

Figure 6. Mean a*/b* values in a) 'Audience' and b) 'Livento' in all light treatments during storage. Bars represent standard deviation. N=10.

Hue

The hue angle decreased steadily in both cultivars (

Figure 7), indicating that the coloration was becoming more red. In 'Audience', tomatoes from the far-red treatment had a significantly higher hue value than the dark treatment on day 0 (P=0.026) and significantly lower than tomatoes from the blue treatment on day 12 (P=0.012). In 'Livento, the hue angle of tomatoes in the blue treatment was higher than the other treatments throughout the storage period, indicating less red color. The tomatoes from the far-red treatment had significantly lower hue values than the dark treatment on day 0 (P=0.010) and day 4 (P=0.012), and lower than the tomatoes from the AP673L treatment on day 8 (P=0.026). On day 15, the hue angle of tomatoes in the blue treatment was significantly higher than in all treatments but the greenhouse treatment.

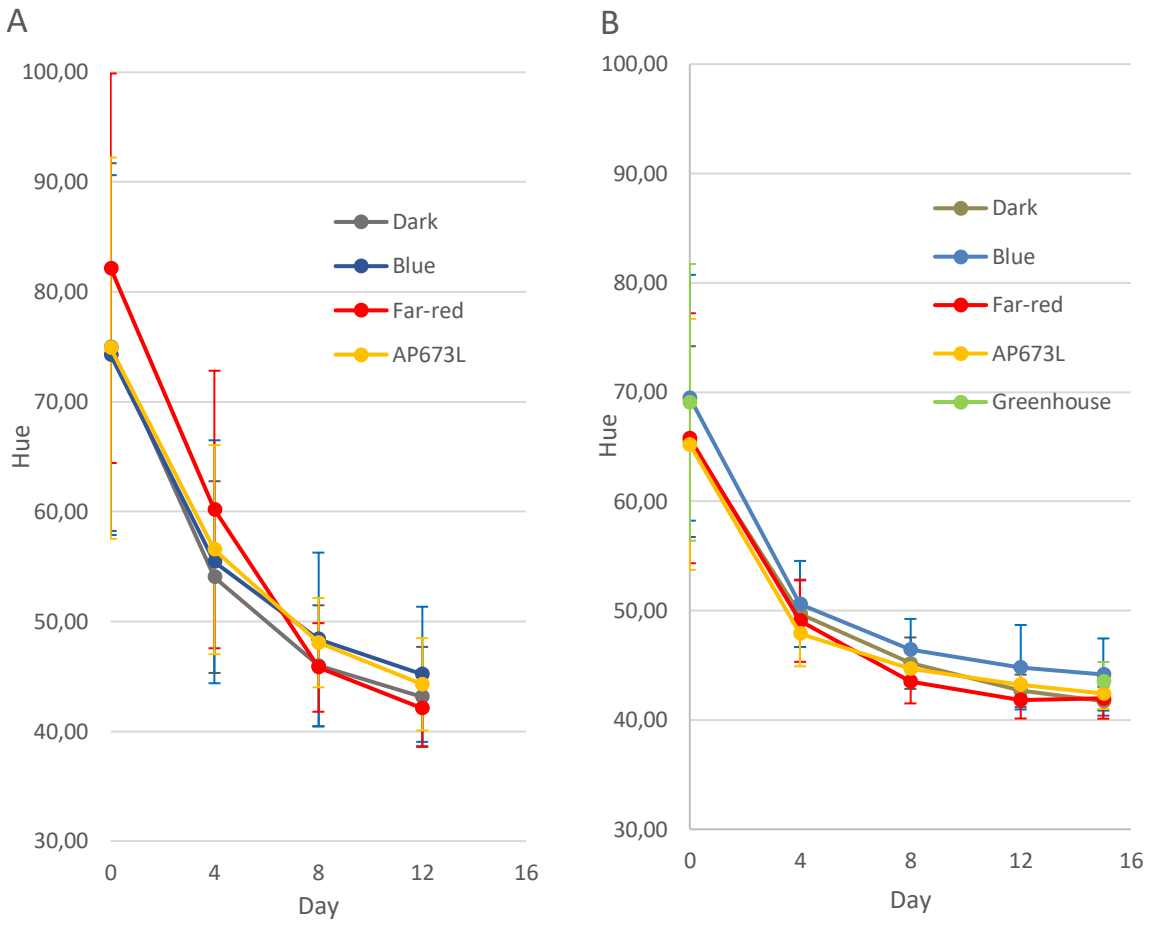

Figure 7. Hue angle in a) Audience and b) Livento. Error bars representing standard deviation. N=10.

Hue angle decreased significantly within all treatments between time points in 'Audience', and in 'Livento' the decrease was significant in all treatments between all the time points except between days 12 and 15 in tomatoes from the blue and far-red treatments, indicating stabilizing of color.

Chroma

Chroma values increased in both cultivars (Figure 8) indicating an increasingly bright color, with values in AP673L and blue treatments being higher than in far-red and dark treatments. Significant differences (P=0.05) could be found in both cultivars between the treatments. In

‘Audience’, tomatoes from the blue treatment had a higher chroma value throughout the storage period, and this was significantly higher than in far-red and control treatments on days 4 (P=0.000) and 8 (P=0.000). On day 12, the chroma value of the tomatoes in the dark treatment was significantly lower than in the blue treatment (P=0.011) and AP673L treatment (P=0.017).

In ‘Livento’, the tomatoes from the AP673L treatment had significantly higher chroma values than the other treatments throughout the storage period. This was not significant only compared to the chroma values of the tomatoes from the blue treatment, apart from day 0 (p=0.042). The chroma value of tomatoes from the far-red treatment was significantly lower to the blue treatment on day 4 (P=0.000), day 8 (P=0.001) and day 15 (P=0.009).

Looking at differences within treatments, it could be seen that chroma values increased significantly between all the time points in ‘Audience’ and stabilized towards the end in ‘Livento’.

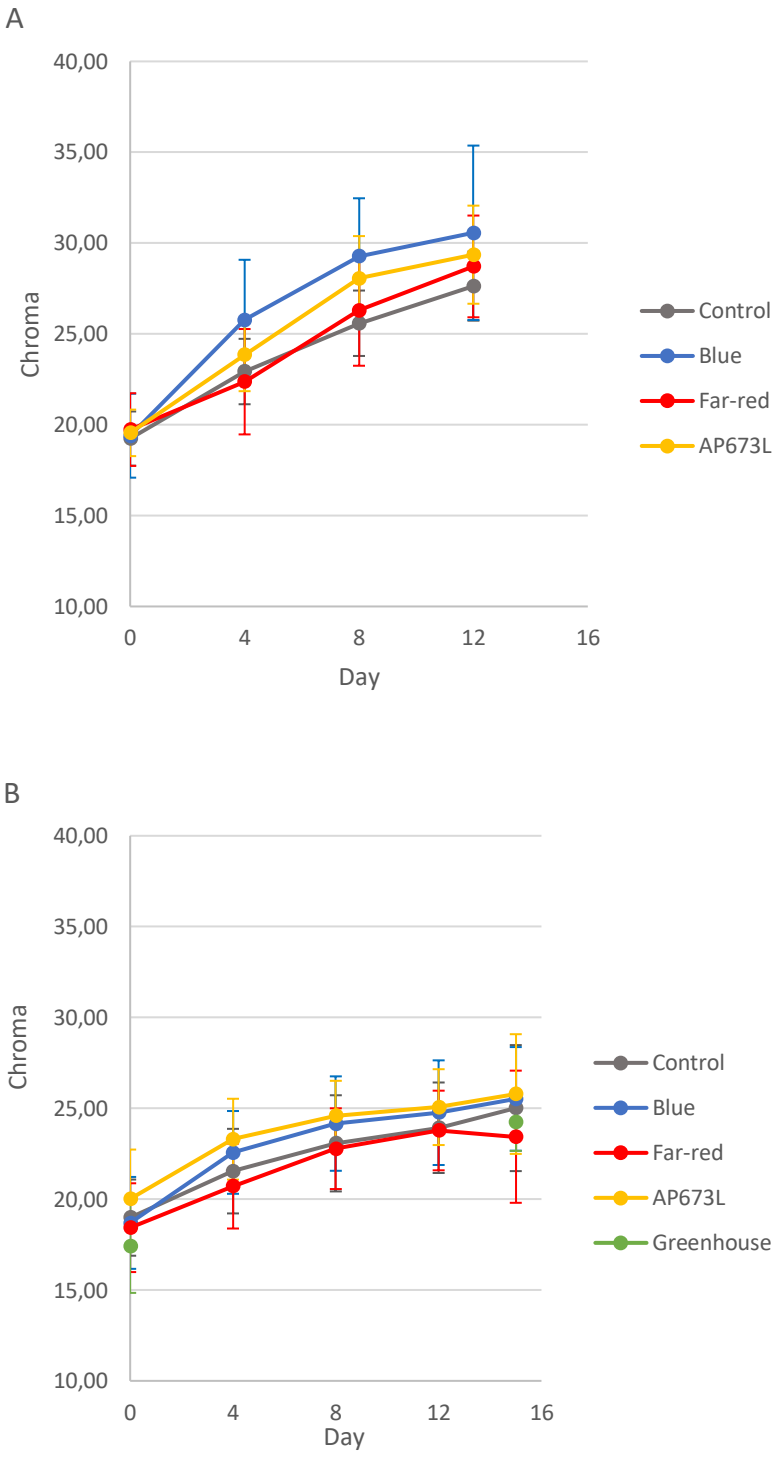

Figure 8. Chroma values in a) Audience and b) Livento. Error bars representing standard deviation. N=10.

5.2 Destructive analyses

5.2.1 Firmness

Firmness decreased gradually in ‘Livento’ in all the treatments over time (Figure 9), and the greatest loss of firmness was in the tomatoes kept in the greenhouse. From the LED-treatments, the most rapid decrease in firmness was observed in tomatoes in the blue treatment, which was significantly lower from the control treatment on day 8 (P=0.042), and far-red treatment on days 12 (P=0.036) and 15 (P=0.003).

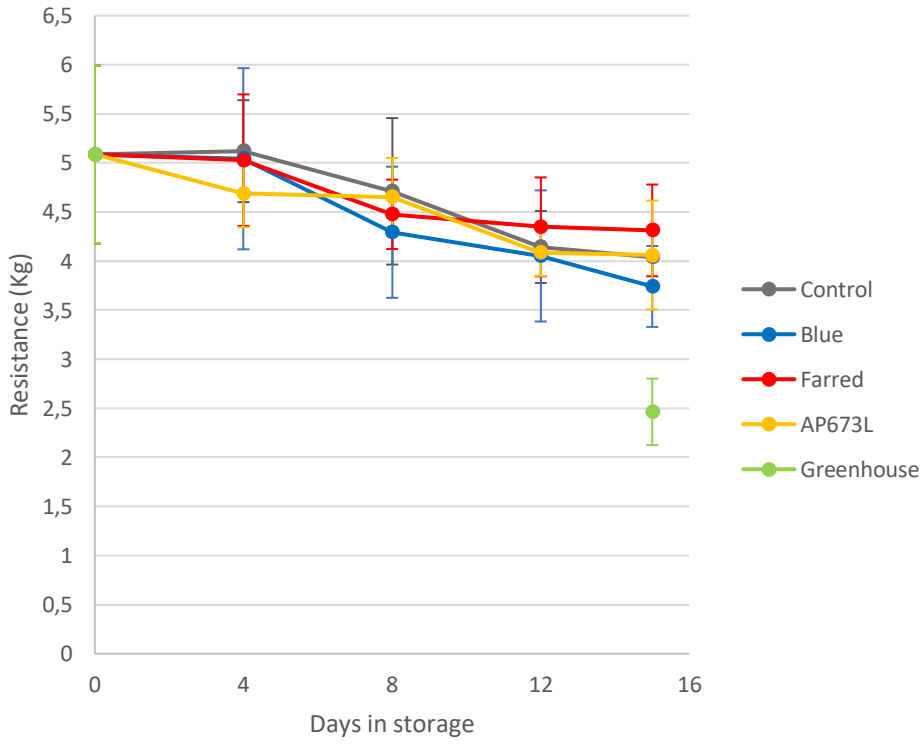

Figure 9. Firmness in ‘Livento’ presented in resistance (kg). Error bars representing standard deviation. N=10.

5.2.2 Lycopene

Lycopene content (mg/100 g) had a significant rise (P=0.005) during storage in both cultivars and in both cultivars an effect of the treatment could be seen.

In ‘Audience’, lycopene content increased significantly over time in all treatments, but the response of the tomatoes differed between all the treatments apart from control treatment and blue treatment (Figure 10a). Tomatoes from AP673L treatment had the highest lycopene content throughout the experiment, and this was significantly higher than in the far-red treatment on day 4 (P=0.004), day 8 (P=0.000) and day 12 (0.028), whereas the lycopene content of tomatoes from the far-red treatment remained the lowest throughout the experiment.

In ‘Livento’ (Figure 10b) significant differences between the treatments could be observed from day eight onwards, when the lycopene content of tomatoes from the blue treatment was significantly higher than the ones from the far-red treatment (P=0.006). The lycopene content of the tomatoes in the control treatment was significantly lower than in the blue treatment on days 12 (P=0.004) and 15 (P=0.002), and on day 15 tomatoes from the AP673L treatment had significantly higher values than in the control treatment (P=0.004).

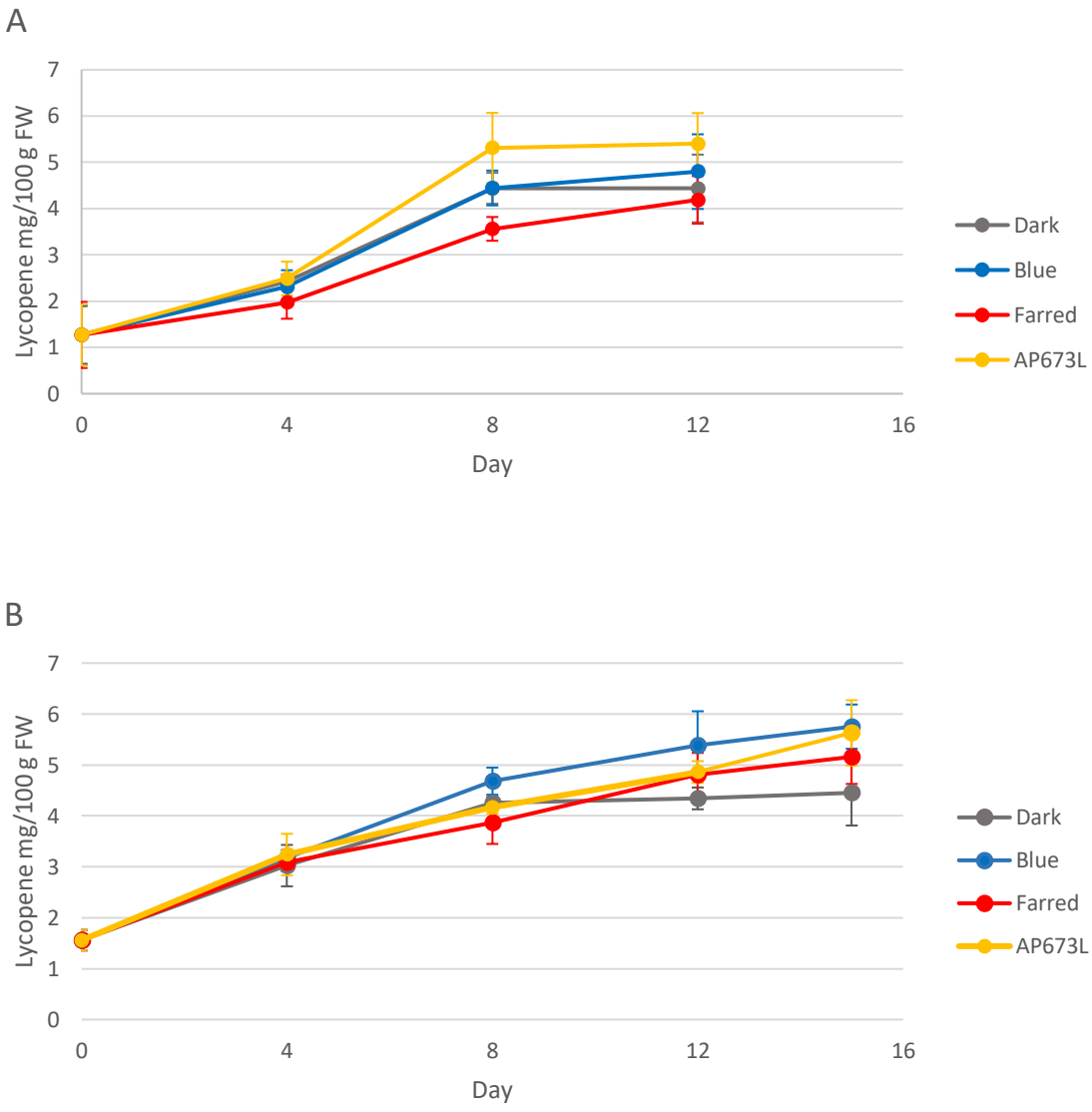

Figure 10. Lycopene content (mg/100 g FW) in a) 'Audience' and b) 'Livento'. Error bars representing standard deviation. N=4.

5.2.3 Vitamin C

In 'Audience', tomatoes from the blue treatment had a significantly higher vitamin C content (Ascorbic Acid in mg/100 ml) than tomatoes from AP673L treatment on day 12 (P=0.021)

(Figure 11). In ‘Livento’ the values remained lower in tomatoes from the control treatment, and this was significant on day 8 compared to tomatoes from the blue treatment (P=0.05) and far-red treatment (P=0.016).

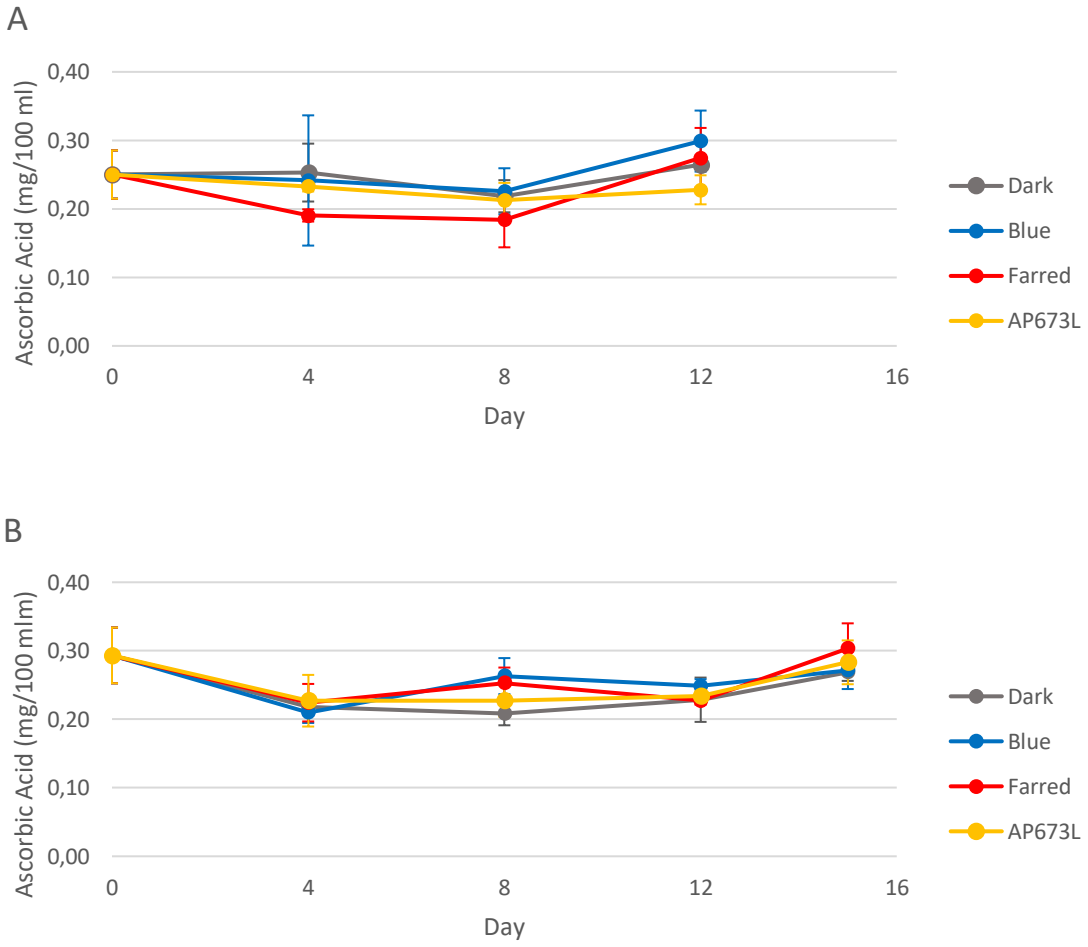

Figure 11. Vitamin C content in Ascorbic acid (mg/100ml) in a) 'Audience' and b) 'Livento'. Error bars representing standard deviation. N=4.

5.2.4 Total soluble sugars and Titratable acidity

Total soluble sugars

In ‘Audience’ TSS values first increased from day 0 to day 4, and then decreased slightly (Table 2). The total soluble sugar content in tomatoes from far-red treatment was significantly lower than blue and AP673L treatments on day 4 and day 8. On day 12, the TSS in tomatoes from AP673L treatment was significantly higher than in far-red treatment. In ‘Livento’, TSS increased in all treatments with tomatoes from AP673L treatment having lower values throughout the experiment.

Table 2. Total soluble sugars expressed as °Brix in both cultivars. Different letters indicating statistical differences between treatments (p=0.005). N=4.

'Audience'												
	Day											
Treatment	0	±		4	±		8	±		12	±	
N/A*	4,70	0,14										
Control				5,05	0,10	ab	5,03	0,05	ab	4,95	0,06	ab
Blue				5,15	0,17	a	5,08	0,10	a	4,90	0,12	ab
Far-red				4,85	0,19	b	4,75	0,25	b	4,75	0,25	a
AP673L				5,15	0,10	a	5,15	0,25	a	5,10	0,20	b

'Livento'															
	Day														
Treatment	0	±		4	±		8	±		12	±		15	±	
N/A*	4,4	0,28													
Control				4,65	0,19	ab	4,70	0,20	a	4,55	0,19	ac	4,65	0,10	ab
Blue				4,75	0,19	a	4,65	0,10	a	4,95	0,10	bd	4,85	0,10	ab
Far-red				4,65	0,10	ab	4,60	0,16	a	4,85	0,19	cd	4,90	0,12	b
AP673L				4,45	0,19	b	4,55	0,30	a	4,55	0,19	ac	4,60	0,33	a

**Not Applicable*

Titratable acidity

The titratable acidity percentage decreased slightly in both cultivars over time (Table 3)

Table 3. Titratable Acidity (TA%) in both cultivars. Different letters indicating statistical differences (p=0.005). N=4.

'Audience'										
	Day									
Treatment	0	±	4	±		8	±	12	±	
N/A*	0,652	0,053								
Control			0,736	0,055	a	0,717	0,020 a	0,640	0,033	a
Blue			0,711	0,050	a	0,717	0,042 a	0,661	0,036	a
Far-red			0,726	0,044	a	0,673	0,048 a	0,663	0,021	a
AP673L			0,750	0,027	a	0,693	0,044 a	0,650	0,035	a

'Livento'													
	Day												
Treatment	0	±	4	±		8	±	12	±		15	±	
N/A*	0,781	0,241											
Control			0,742	0,028	a	0,696	0,004 a	0,614	0,035	a	0,686	0,069	a
Blue			0,714	0,062	a	0,697	0,006 a	0,679	0,033	b	0,678	0,023	a
Far-red			0,686	0,039	a	0,684	0,038 a	0,661	0,045	ab	0,690	0,020	a
AP673L			0,718	0,085	a	0,732	0,198 a	0,635	0,042	ab	0,671	0,063	a

**Not Applicable*

The TSS/TA% ratio had some fluctuations in both cultivars (Table 4). Significant differences could be observed in ‘Audience’ on day 12, when the TSS/TA% ratio was significantly higher in tomatoes from AP673L treatment than the other treatments and significantly lower in tomatoes from the far-red treatment.

Table 4. TSS/TA ratio in both cultivars. TSS expressed as °Brix. Different letters indicating statistical differences (p=0.005). N=4.

Brix°/TA% – 'Audience'

	Day									
Treatment	0	±	4	±		8	±	12	±	
N/A*	7,227	0,366								
Control			6,887	0,380	a	7,014	0,155 a	7,744	0,392	ab
Blue			7,272	0,547	a	7,093	0,314 a	7,429	0,513	ab
Far-red			6,708	0,586	a	7,087	0,617 a	7,168	0,440	a
AP673L			6,874	0,249	a	7,434	0,208 a	7,851	0,292	b

Brix°/TA% – 'Livento'

	Day											
Treatment	0	±	4	±		8	±	12	±		15	±
N/A*	5,632	0,031										
Control			6,271	0,177	a	6,798	0,367 a	7,434	0,554	a	6,848	0,889 a
Blue			6,679	0,453	a	6,675	0,132 a	7,302	0,220	a	7,156	0,202 a
Far-red			6,803	0,533	a	6,732	0,194 a	7,356	0,411	a	7,103	0,290 a
AP673L			6,254	0,674	a	6,583	1,890 a	7,179	0,463	a	6,878	0,492 a

**Not Applicable*

5.3 Correlations

Initial weight & weight loss

No correlations were found between the initial weight of the tomatoes and their weight loss percentage.

Color & lycopene

A positive correlation could be seen in the average values of color development and lycopene accumulation in both cultivars (Figure 12). When the a*/b* value increased indicating redder color, also the lycopene content increased.

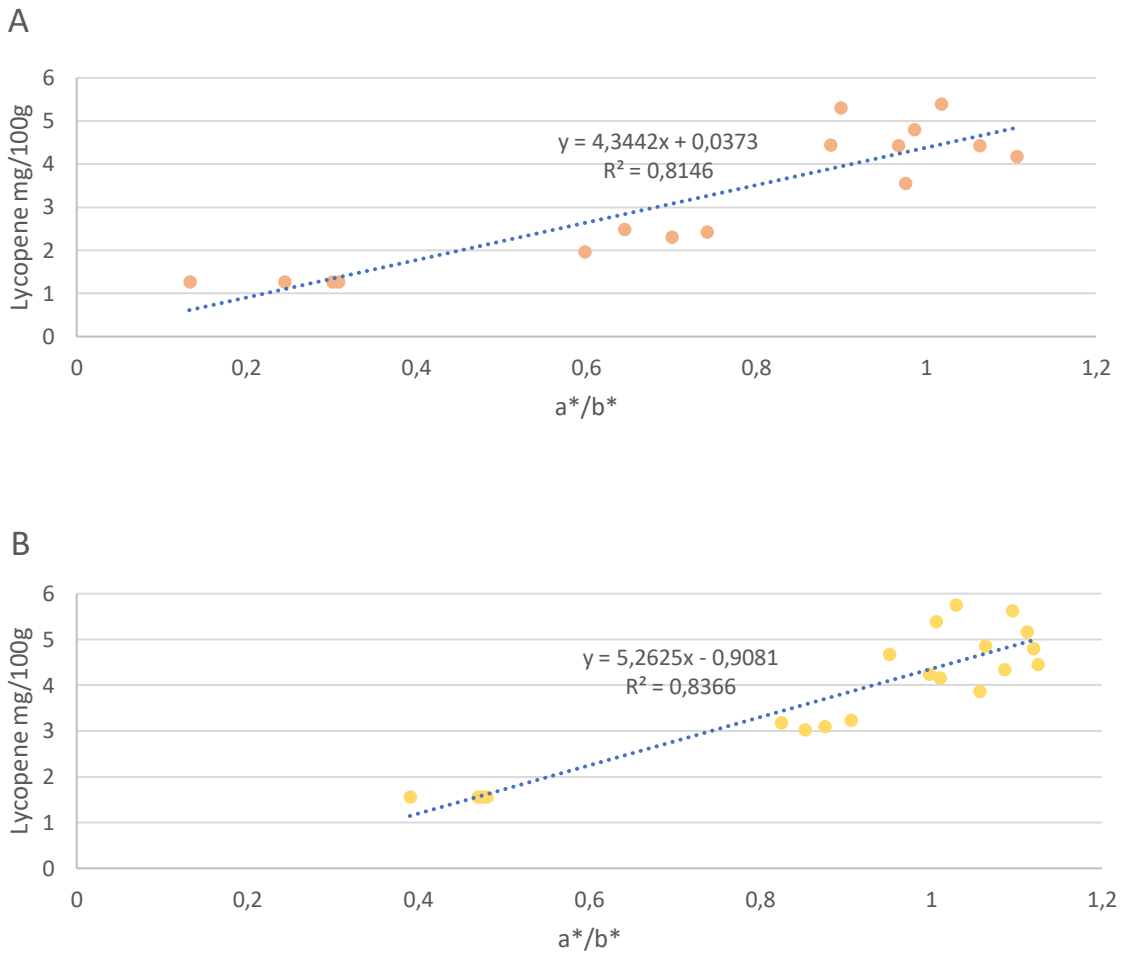

Figure 12. Correlation between a*/b* value and lycopene in a) Audience (N=10) and b) Livento (N=16).

Firmness and weight

A positive correlation could be seen between firmness and weight loss (Figure 13). The peak resistance (kg) decreased simultaneously with decrease in weight (%).

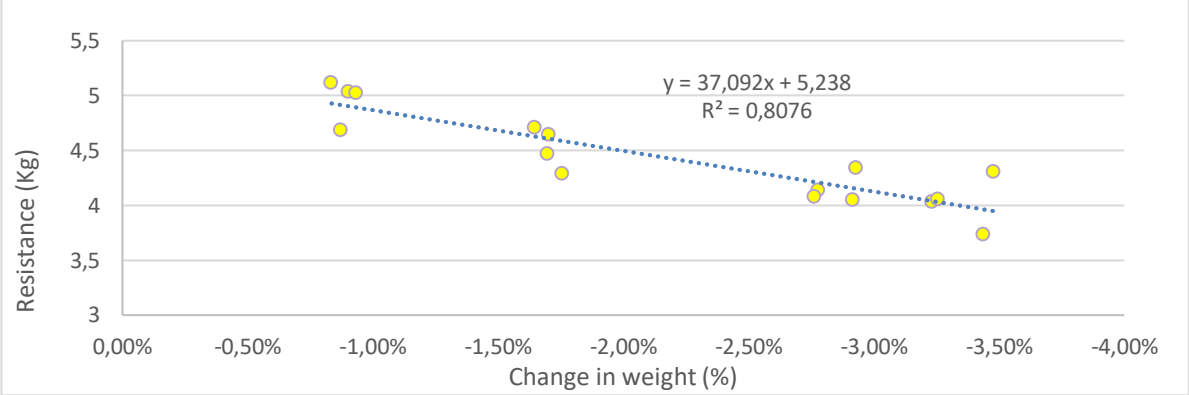

Figure 13. Correlation of firmness (in resistance (kg)) and weight decrease (%) N=16

5.4 Taste panel

A taste panel was organized for 'Livento' after 15 days in storage. The participants were asked to assess the sweetness, acidity, mouthfeel, structure and of the tomatoes as well as to give an overall score (1–5) for the tomatoes (Figure 14). The model for the answering sheet can be found in Appendix 1.

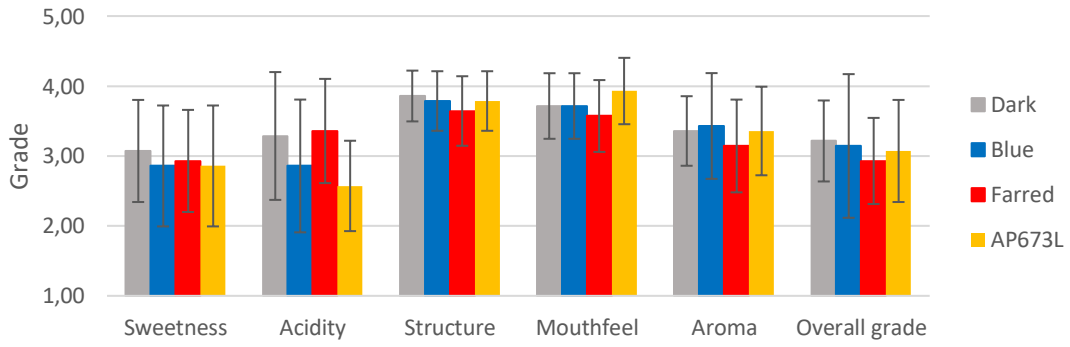

Figure 14. Taste panel results for 'Livento'. Error bars represent standard deviation. N=14

6 Discussion

Weight and firmness

In the present study the potential effect of post-harvest LED–lighting on the tomato quality characteristics was studied. Regarding the external quality, it is not certain whether light treatments had a significant effect on fruit weight, but it seems light played a role in color development.

Weight decreased steadily in all treatments in both cultivars and the weight loss was more rapid in ‘Audience’ than in ‘Livento’. This is likely due to the fact that ‘Audience’ was less mature, and experiencing a respiration peak resulting in higher weight loss, whereas in ‘Livento’ respiration had already started to decrease (Gustafson 2019). Regarding treatment effects, the most rapid loss in ‘Audience’ was observed in the dark treatment, whereas in ‘Livento’ the total loss was the largest in the tomatoes from the far-red treatment.

No correlations were found between the initial weight of the tomatoes and their weight loss percentage, indicating that the size of the tomatoes is not related to their respiration rates. This is controversial to what i.e. Todd et al, 1960 deducted; respiration rates are higher in larger fruit, which indicates that weight loss should be larger in fruit with higher initial weight. The tomatoes kept in the greenhouse had a significantly higher weight loss compared to the LED-treatments, but this is likely to be also contributed by temperature, which was above 20°C and the effect of light cannot be solely determined. The same applies for firmness, as the tomatoes kept in the greenhouse had a more significant total loss of firmness compared to the other treatments. This is supported by previous findings, where high temperatures were seen to affect firmness of fruit negatively (Tadesse et al. 2015). From the led–light treatments, firmness was lost most rapidly in the tomatoes kept in the blue light treatment and remained the steadiest in far-red treatment. This is supported by the findings of Dhakal and Baek (2014) who observed blue light to have a softening effect on tomatoes. Blue light has also been seen to have an inducing effect on ripening in banana (Huang et al. 2018) and increasing ethylene production in broccoli (Ma et al. 2014). Further, to support the present findings, where far-red treatment was seen to decrease the loss of firmness, also Ma et al (2014) observed decreased ethylene production in broccoli with red light treatment.

Nájera et al (2018) observed AP673L treatment to keep the tomatoes firm, but this was not seen during the present study, where AP673L treatment was comparable to the control treatment. Firmness seems to be related firstly to temperature, but also to photosynthetic activities through stomatal activity and ethylene production, and i.e. Huang et al (2018) also concluded that dark storage is the most suitable for delayed loss of firmness.

Color

Looking at changes in color, the tomatoes did, as expected, become more red (increasing a*/b* –values, decreasing hue angle). The a*/b* ratio, which is in general accepted as a good parameter for tomato marketable color, increased significantly within the treatments, and most rapidly in tomatoes in the far-red treatment in both cultivars. Hue angle, which is also commonly used for indicating red color, also increased significantly within treatments between different time points. No significant differences could be seen between the light treatments when comparing the treatments on a time–point basis in 'Audience', but in 'Livento' it seemed that in tomatoes from blue light treatment the hue angle decreased less than in the other light treatments, indicating less red coloration. However, the tomatoes in the blue light treatment had already higher values during the initial measurements, which is likely to have affected the subsequent measurements. Tomatoes from the far-red treatment had the lowest hue angle values, suggesting that far-red would contribute to the development of red color, matching the a*/b* ratio results. Further, looking at the values within treatments between time points, it seems that color development started stabilizing after 12 days, suggesting that the deepest color was reached. Chroma values increased in both cultivars steadily indicating brightening color, and in both cultivars, it could be seen that tomatoes from the blue and AP673L treatments had the highest chroma values, whereas far-red had the lowest.

Dhakal and Baek (2014) concluded that dark and red-light treatments were inducing red coloration. In the present study, it seems far-red had a more influential effect on the development of color. Further, in 'Audience' chroma increased significantly within the treatments between all time-points, whereas in 'Livento', no significant differences could be observed from day 8 onwards, suggesting that color development stabilized towards the end

of the experiment, which was also seen in the hue angle results. Differences between the cultivars are likely to be explained by the developmental stage of the fruit, as ‘Livento’ had a more developed initial coloration. The same applies to the standard deviation, which was high at the beginning of the experiment, especially in ‘Audience’. Decreasing standard deviation indicates that the tomatoes became more evenly colored, and at the end of the storage, SD was comparable in both cultivars.

Lycopene

Differences between the treatments could also be seen in the inner quality analyses. Lycopene content increased significantly over time in both cultivars, but the effect of treatment was not completely clear. It could, however, be seen that far-red and control treatments had the lowest lycopene contents in both cultivars at the end of the experiment. Alba et al (2000) and Nájera et al (2018) suggested that far-red treatment has a reversing effect on the lycopene content, which is supported by the findings of the present study. Additionally, tomatoes from AP673L treatment (with high R:FR), had the highest lycopene content on the last observation day in both cultivars. This goes accordingly to the findings of Nájera et al (2018), Alba et al (2000), Panjai et al (2017) as well as Dhakal and Baek (2014), which all found in their studies that red light has an increasing effect on the lycopene content of tomatoes. Also Ma et al. (2012) observed increasing carotenoid content with red light treatments in citrus, whereas blue light was not seen to have any effect. In the present study, however, blue light seemed to have an increasing effect on the lycopene content in the cultivar ‘Livento’. In ‘Audience’ the response was not as high but blue light had also a positive effect on lycopene.

This could have to do with increased ethylene production, which has been seen to have a positive correlation with lycopene accumulation (Boe & Salunkhe 1967). Ethylene was not measured in the present study, but previous studies (Dhakal & Baek 2014; Ma et al. 2014; Huang et al. 2018) propose blue light to have an increasing effect on ethylene production, which here could have correlated further with lycopene accumulation.

Differences in treatment responses of the tomatoes could be caused by genetics, but also initial storage conditions. As ‘Livento’ had a more mature development stage during harvest,

the fruit were stored in colder temperature (7°C) than ‘Audience’ (12°C). Colder temperatures could have halted the maturation processes of ‘Livento’ and affected the lycopene accumulation, which has seen to be positively affected by higher temperatures (Khairi et al. 2015).

Color development correlated positively with the lycopene content, which is supported by previous studies (Brandt et al. 2006; Barrett & Anthon 2008). It is still, however, unclear, what spectrum of light contributes to these values, as lycopene content was mainly affected positively by red light, whereas the major contributor to color seemed to be far-red.

Ascorbic acid

Ascorbic acid (AsA) contents were unexpectedly low during the experiment, ranging around 0.2–0.3 mg/100 ml. The method used is a common one, but there might have been errors in the mechanical titration. Detection of the end–point during the titration proved to be challenging, due to its subjectivity. Other human errors during reading the results or preparing the solutions are also possible (Titrations.info 2011). As the measured AsA contents were so much lower than expected, it could also be that the AsA was already oxidized into dehydroascorbic acid (DHA) as filtration took time (Van Bree et al. 2012; Munialo et al. 2014). In strawberry, it was shown that a strong linear reduction of vitamin C takes place and almost all AsA is oxidized after 8 hours. (Sapei & Hwa 2014). Van Bree et al, (2012) had similar observations, and it seems that AsA indeed degrades in a very short time. In the present study samples were analyzed on average five hours after homogenization leaving only a fraction of vitamin C left. Additionally, the samples were stored in room temperature. Sapei, & Hwa (2014) concluded that lower temperature slowed down the degradation of AsA. Future AsA analyses should include a more stable and reliable method, such as the use of HPLC analyses with detection of total vitamin C activity, including DHA analysis, or the use of oxalic acid to prevent atmospheric oxygen from oxidating the AsA (University of Canterbury 2018).

Total soluble sugars and titratable acidity

The total soluble sugars were at expected levels, ranging around 4-5 ºBrix but the treatment responses had differing results between the cultivars. In 'Audience', tomatoes from AP673L treatment were observed to have the highest TSS value, followed by tomatoes from the blue treatment. This goes accordingly to the findings of Panjai et al (2017) and Nájera et al (2018), which both observed red light to have an increasing effect on TSS. Further, Lei et al (2016) found a combination of red and blue light to increase the amount of total soluble sugars, so it is possible that the high brix values of blue light treatment go in accordance to their findings. However, in 'Livento', the results were quite the opposite, as tomatoes from AP673L treatment had a significantly lower brix value than far-red treatment, which had the highest values. Blue light treated tomatoes had, however higher values in 'Livento' as well. It is possible, that these differences are due to the different cultivars used (Nájera et al. 2018), but also due to the differences in ripening stage at the beginning of the experiment.

It could also be that TSS is not affected by light (Dhakal & Baek 2014), but rather by other factors such as ethylene, like observed by Boe and Salunkhe (1967), or preharvest factors. Environmental and cultural conditions preharvest, such as EC (and related water stress) and light conditions affect sugar accumulation especially in young fruit as the starch content increases and therefore the sink strength becomes higher. An early harvest causes insufficient sugar accumulation (Beckles 2012), which suggests that the total soluble sugars accumulation is indeed affected by the starch accumulation of the younger fruit. Results of previous studies (Yelle et al. 1988; Dinar & Stevens 1981 ref. Garvey & Hewitt 1991) have suggested that fruit with higher initial starch content have later a higher sugar content, and therefore it could be, that TSS is affected more during pre– than post-harvest. The TA% was ranging around 0.7%, which can be thought to be an acceptable level, but no clear responses to the treatments could be observed.

It seems that many of the shelf life characteristics are largely affected by light but also the storage temperature. In the present study this was optimized, but the relative humidity was lower (65±5%) than recommended (85%). This could have affected the results of the analyses, especially firmness and weight loss.

The taste panel conducted was very small, and no strong conclusions can be drawn, but based on it none of the tomatoes were of outstanding flavor. Increasing brix and acidity is still one major goal when looking at the future, as consumer preference largely based on them. Nutritional value is rarely tasted even though red tomatoes seem more attractive to consumers, and indirectly it could be tomatoes with higher lycopene content are preferred.

7 Conclusions

Looking at the results of the present study, light clearly has an effect on both outer and inner post-harvest quality characteristics of tomato. The exact effects of treatments could, however, not be determined with all the characteristics. This could possibly be because of the different cultivars used, but also their different development stages. Further, previous studies have used light flashes, whereas in the present study the light treatments were continuous. Looking at a practical application of the results, it is also more likely that the light treatments would be for shorter periods, e.g. in a supermarket during the night. Also, as the responses are different at different development stages, for future studies this should be taken in to consideration. Instead of continuous light, alternating light/dark periods could be considered, or changing the light spectrum during storage, depending on the desired result, as different responses for different spectrums could be observed.

Blue light seems to have an enhancing effect on the ethylene production, and therefore if more effective ripening is desired, blue light is recommended. Blue light decreases firmness but seems to increase lycopene. Lycopene accumulation is also enhanced by a high red to far-red ratio. Both blue and AP673L treatments also increased the chroma values, making the tomatoes brighter in color.

Far-red seems to enhance red color development and retain firmness, but to decrease lycopene accumulation and to make the color duller.

Tomatoes kept in the dark had low lycopene content and a dull coloration. Currently tomatoes are often stored in dark, and consumers consider them of low quality. This could be due to the duller coloration, but also lower nutritional values.

Clearly, post-harvest light treatments could improve the post-harvest quality of tomatoes and make them more appealing and more nutritious.

For further research, more cultivars of tomatoes with a comparable developmental stage should be considered to see the effect of genotype on the responses for light. Further, the effect of temperature could be included to see how the interaction of light and temperature affects the characteristics studied. Studying ethylene levels and their development during storage could give good indications on how post-harvest technology could be improved.

Ethylene studies could also include the use of 1-MCP. Future studies should also include the examination of the development of these characteristics while the fruit is still attached to the plant in order to see the effect of cultivation methods on the responses of additional LED lights on the chosen cultivars.

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Appendix – Taste panel answer sheet

Tomato (circle): A B C D					
Sweetness	5 Very sweet	4 Sweet	3 Not very sweet	2 Not sweet	1 Not at all sweet
Acidity	5 Very acidic	4 Acidic	3 Not very acidic	2 Not acidic	1 Not at all acidic
Structure	5 Very good	4 Good	3 Satisfactory	2 Bad	1 Very bad
Mouthfeel	5 Very good	4 Good	3 Satisfactory	2 Bad	1 Very bad
Overall	5 Very good	4 Good	3 Satisfactory	2 Bad	1 Very bad
Aroma	5 Very good	4 Good	3 Satisfactory	2 Bad	1 Very bad
Other comments					